Phase Locking of a Second Harmonic Gyrotron using A Quasi-optical Circulator

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ABSTRACT

Phase locking of a high power pulsed gyrotron oscillator through the use of a quasi-optical circulator was investigated. A second harmonic gyrotron which features a nod complex cavity, operating at 34.5 GHz, was used in the experiment. The quasi-optical circulator consisted of a 5.75" diameter ferrite disk biased with a one kilogauss permanent magnet. A polarizing grid was used to separate the input and output signals in the circulator. In order to couple the gyrotron oscillator output efficiently to the quasi-optics system, a number of mode converters, TE_{03}-TE_{02}, TE_{02}-TE_{01}, TE_{01}-TM_{11}, and TM_{11} - HE_{11}, were required. The insertion loss of the circulator and mode converter chain was approximately 1 dB, and an isolation exceeding 25 dB was achieved. In addition, a low power WR28 waveguide isolator was inserted in the injection signal path, providing an additional 35 dB of isolation, for a total isolation of 60 dB. The injection signal was provided by a synthesized signal generator and a 100 Watt travelling wave tube amplifier. A sample of the gyrotron output signal was obtained through an additional horn and mixed with a sample of the injection signal, producing a difference signal. The injection signal was swept slowly through a known frequency range while the difference signal was recorded. The recorded signals were analyzed off-line, and the locking bandwidth was determined. Experiments were performed for injection powers from 0-60 Watts, and a gyrotron output power of approximately 80-100 kW. Phase locking was observed for all non-zero injection powers.

1 INTRODUCTION

The benefits of high power millimeter wave radiation for use in communication and radar systems are well known. Recently a frequency allocation near 35 GHz has been made for deep space communications, including bands for both spacecraft uplink and downlink. Traditionally these bands have also been used for planetary radar, and for radio science experiments with deep space probes. For many radar and radio science experiments high power uplink signals, on the order of hundreds of kilowatts CW, are attractive. Presently no amplifiers are available for producing such uplink power levels at 35 GHz. There are however gyrotron oscillators producing up to 200 kW CW at 28, 35, and 60 GHz. These oscillators, developed primarily for ECRH heating of plasmas in fusion reactors, have not seen widespread application outside this field. One primary reason is that they are indeed oscillators, incoherent sources of radiation. Radar systems, particularly those used for planetary radar long term stability due to the large round trip light times involved, several hours for a radar study of Saturn's rings, for example.

In view of the lack of amplifiers available at 35 GHz, and the availability of gyrotrons, a study was undertaken to determine whether an injection locked gyrotron oscillator could meet the performance requirements of a radar system or a radio science experiment.[1] Of primary concern is the available bandwidth over which the oscillator can be locked. Planetary radar systems require approximately 10-20 MHz of bandwidth while some radio science experiments are run essentially CW, but requiring very high long term stability. For such applications it appears that an injection locked gyrotron is a viable source.

Next the technical problem of designing a system capable of injection locking a gyrotron was considered. Previous work in this area employed conventional waveguide circulators, and was sufficient to demonstrate locking[2] in a pulsed system. Such a system is not scalable to 200 kW CW, however. Practical problems include cooling the circulator, and dealing with the fact that gyrotrons emit their output power in highly overmoded waveguides where conventional circulators cannot be employed. In order to circumvent these problems a new approach, using a quasi-optical circulator[3] to isolate the injection and output signals was considered. The quasi-optical circulator can be scaled to very high power levels, and operates in free space as opposed to in a waveguide, thus eliminating the problems associated with conventional circulators.

In this paper we describe a joint experiment between the Jet Propulsion Laboratory (JPL) and the Institute for Plasma Research (IPR) at the University of Maryland in which a pulsed second harmonic gyrotron operating at 35 GHz was injection locked to a low power synthesized source using a quasi-optical circulator. The circulator, mode converters, beam waveguide system and instrumentation were provided by JPL, while the gyrotron and theoretical predictions were handled by IPR. The experiment demonstrates for the first time injection locking of a gyrotron using a quasi-optical circulator, and is also the first reported injection locking of a second harmonic gyrotron by any means. The following sections will describe the experimental configuration, giving details regarding each component, the theory governing the experiment, and the experimental results.

2 EXPERIMENTAL CONFIGURATION

The experimental configuration depicted in block diagram form in Figure 1. A low power signal is amplified and feel through a conventional isolator and quasi-optical circulator into the gyrotron. Samples of the: injection signal and high power output signal are compared using a mixer and examined for phase locking behavior.

The physical layout of the experiment is shown in Figure 2, The injection signal is launched into the beam waveguide system using a conventional horn. It is focused by an ellipsoid, and polarized in such a direction as to reflect off a polarizing grid. The signal then passes through tile Faraday rotator where it undergoes 45 degrees of polarization rotation. It is then focussed into the end of the mode converter chain connected to the gyrotron. The injection signal then enters the gyrotron cavity and phase locks the high power signal emitted by the gyrotron. This high power output signal then passes back out the mode converter chain and through the Faraday rotator where it undergoes an additional 45 degrees of polarization rotation. At this point the high power signal is polarized at 90 degrees to the injection signal, and hence it passes through the polarizing grid. The quasi-optical circulator achieved 25 dB of isolation from 34 to 35 GHz. The measured insertion loss for the beam waveguide system including spillover loss, horn loss, mode converter loss, reflection and transmission loss in the Faraday rotator, and alignment loss was approximately 1 dB].

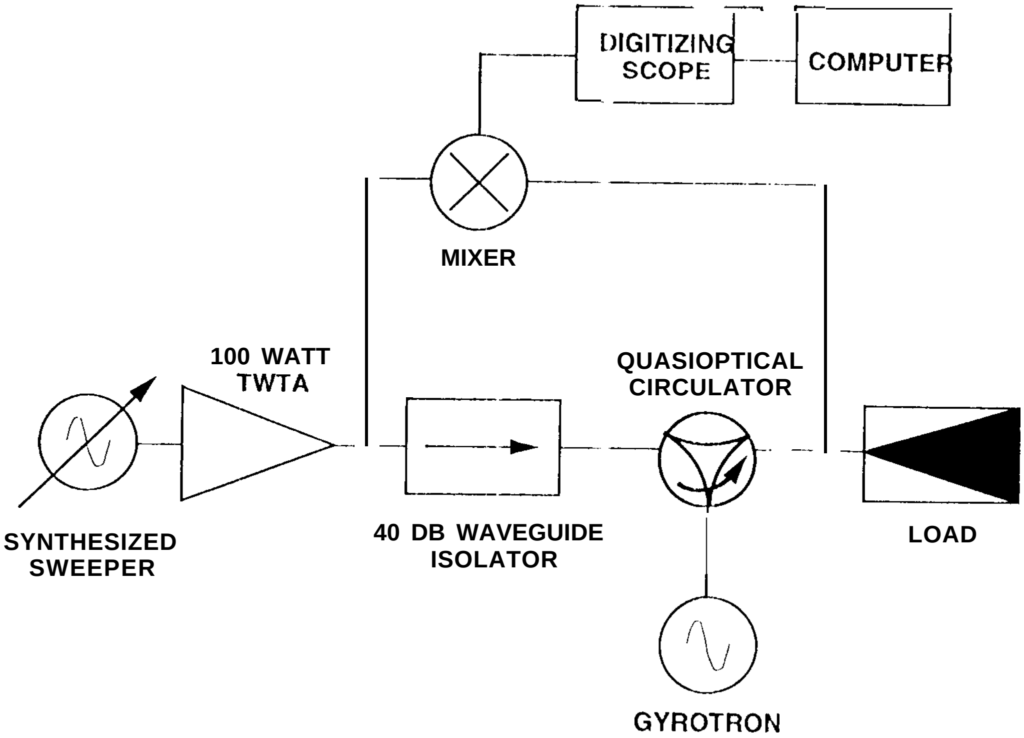

Figure 1: Experimental block diagram.

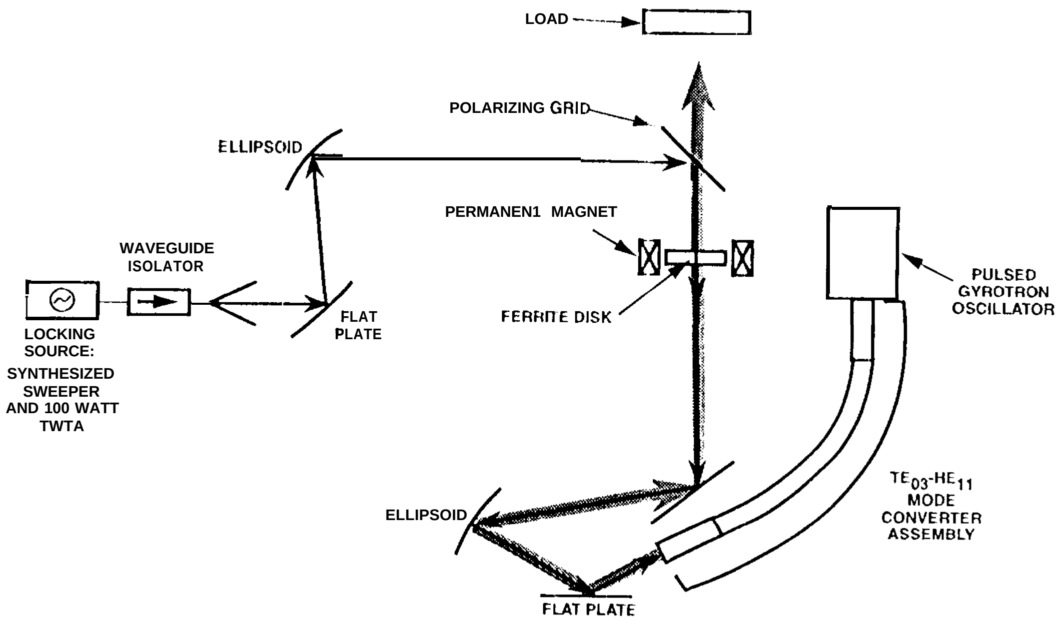

Figure 2: Experimental configuration.

2.1 Gyrotron

The gyrotron used for this experiment is a GY-32 second harmonic gyrotron[4] employs a unique complex cavity which provides high output mode purity, and stable, efficient harmonic operat ion. The gyrotron's operating parameters for this experiment arc shown in Table 1

Parameter	Value
Harmonic Number	2
Beam Voltage	42-45 kV
Beam Current	8 A
Frequency	34.52 GHz
Output Power	80-100 kW
Repetition Rate	43 Hz
Pulse Width	7 μs
Output Mode	TE_{03}

Table 1. GY-32 operating parameters

2.2 Mode Converters

As can be seen from Table 1, the GY-32 emits its radiation in the TE_{03} mode. If the power is to injected into the beam waveguide system as shown in Figure 2, it, must be in the form of a Gaussian beam. Transformation of the TE_{03} mode into a Gaussian beam is achieved through the usc of severa 1 mode converters. Due to geometrical and mechanical considerations a mode converter system similar to that considered by Doane,[5] was employed.

The 1.970 inch diameter output waveguide of the gyrotron was nonlinearly tapered to 1.400 inches, where a 4 ripple TE_{03}-TE_{02} mode! converter was inserted. A further tapei to 1.00 inches in diameter was included and followed by a 4 ripple TE_{02}-TE_{01} mode converter. The conversion efficiency of these dc~'ices each exceeded 96 percent. The guide was then bent through an angle of 54.5 degrees over an arc length of 20.() inches converting the TE_{01}]JIc)clctc)tllc'J'hi$_{11}$ mode. Since the bend used a sinusoidal curvat ure dist ribution rather than a constant radius of curvature an efficiency of 99.9 percent was achieved. Finally a corrugated TM_{11}-HE_{11} mode converter and horn assembly was used to generate a Gauss ian beam with t he correct waist size to couple into the beam waveguide system.[6] The measured radiation pattern at, the output of the mode converter chain is shown in Figure 3. Excellent symmetry, low sidelobes, and negligible cross polarization were observed.

2.3 Locking Source

The locking signal was provided by a Wiltron **67401-1** synthesized signal generator and a 100" Watt travelling wave tube amplifier. Although both components are capable of operating CW, they were pulsed for this particular experiment. The synthesizer was triggered to step across a specified frequency range automatically at the start of each experiment.

2.4 Waveguide **Isolator**

In order to provide additional isolation beyond that of t he qua si-optical ci culator a conventional low power waveguide (WR28) isolator was included in the injection signal pat h. It provided an additional 35 dB of isolation

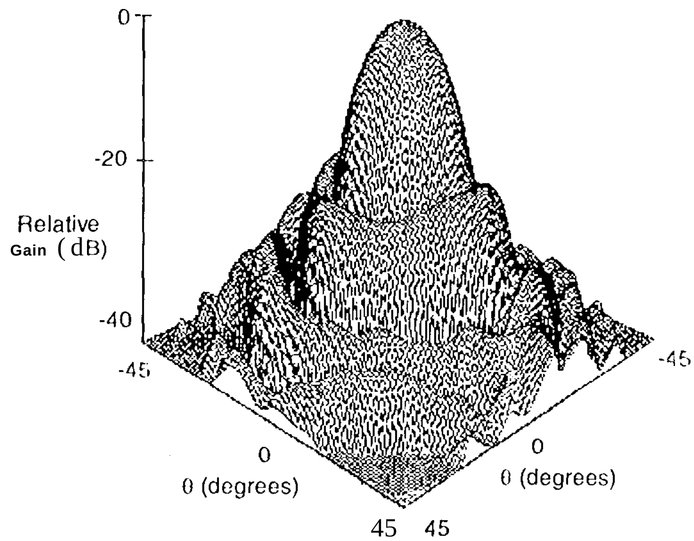

Figure 3: Radiation pattern at the output of the TM_{11}-HE_{11} mode converter.

throughout, the frequency range of the experiment.

2.5 Beam Waveguide System

The injection signal and high power gyrotron signal are launched into a beam waveguide system consisting of two ellipsoids and a number of flat mirrors. The ellipsoids are designed for a 60 degree angle between the incident and reflected beams. The mirrors, injection horn, and gyrotron mode converters are designed to keep the spillover loss past the two ellipsoids under 2%. One focal length of each ellipsoid is 24 inches and this focal point is located at either the phase center of the injection horn or the TM_{11}-HE_{11} mode converter. The second focal length is 48 inches, and this focal point is located in the center of the quasi-optical circulator for both ellipsoids. Thus the two ellipsoids focus the gyrotron output signal and the injection signal to the same point in the center of the ferrite disk/magnet combination.

2,6 Polarizing Grid

The injection signal is polarized so that it reflects off' a polarizing grid after being focused by the ellipsoid. The grid was fabricated by printing ().[)()615 inch copper strips 0110.0123 inch centers on a (),189 inch thick disk of fuzed quartz. Signals polarized perpendicular to the strips pass through the grid with negligible reflection. It should be noted that no arcing was observed in the grid for signals levels up to at least 80 kW peak.

2.7 Faraday Rotator

The Faraday rotation part of the circulator consists of a 5.75 inch diameter disk of ferrite material, TransTech G-4259, biased with a 1 kilogauss NDFE permanent magnet. The thickness of the disk was chosen to be 0.344 inches, producing 45 degrees of Faraday rotation as the microwave beam as it passes through the disk. Fused quartz matching layers of thickness 0.0425 inches were employed on each side of the ferrite disk in order to match to free-space.

2.8 Instrumentation

A sample of the gyrotron output power was obtained through a small horn near the free space load. This signal entered the test port of a mixer, and was mixed with the injection signal. At the mixer output port the instantaneous phase difference between the test and reference signals is thus obtained. This signal is fed into a LeCroy 93141, 1 00 Ms/s digitizing scope, and the scope data was in turn extracted by a computer and stored for later analysis.

3 THEORY

In this section a short summary of the theory governing this experiment is given. A detailed derivation of the equations and a discussion of the effect of beam voltage stability may be found in Gou et al.[7]

3.1 Adler's Equation

The locking effects to be measured by this experiment are described by Adler's equation,[7]

$$\Delta_f = \frac{2f_0}{Q}\sqrt{\frac{P_{in}}{P_{out}}}, \tag{1}$$

Here P_{in} is the injection power which took on values of 0, 6, 15, 30, and 60 Watts for the experiments performed. P_{out} is the gyrotron output power which is assumed to be 100 kW. The nominal frequency of the gyrotron, f_0, is 34.52 GHz, and Δ_f is the *full* locking, bandwidth. Finally, Q is the external quality factor of the gyrotron cavity, and is assumed to be 2500.”

A simple formula also exists for the phase difference between the injection and output signals over the locking bandwidth.

$$\Delta\theta(f) = \arcsin\left(\frac{2(f - f_0)}{\Delta_f}\right). \tag{2}$$

This formula indicates that the locking phase rotates from -90 degrees to +90 degrees as f swings through the full lock bandwidth, $\Delta_f/2 \leq (f - f_0) \leq \Delta_f/2$. Since no effort was made to match the lengths of the injection sample and output sample waveguides the observed phase difference should begin at some arbitrary value when locking is first achieved and then traverse 180 degrees as the frequency of the injection signal is swept through the full locking bandwidth. This relationship will be important in demonstrating that phase locking was accomplished during the experiments.

3.2 Theoretical Waveforms

The lock range is determined by sweeping the synthesizer frequency, j,, across the nominal operating frequency of the gyrotron, f_0, and viewing the difference frequency, Δf, from the mixer. The mixer voltage swings between +V volts and - V volts as the phase difference between the test and reference signals swings between 0 and 180 degrees, and the mixer output is 0 volts when the signals are in phase quadrature, 90 degrees apart. The average value of the phase difference between the reference and test signals over a given pulse is estimated by computing the average of a set of samples taken from the center portion of the difference pulse.

When the difference frequency is large, many cycles appear across the pulse and the average voltage is zero. When the two input frequencies to the mixer are close enough so that no significant portion of a cycle appears across the pulse a finite average voltage between +V and - V is found for that particular pulse. If the injection signal is so close to the gyrotron frequency that the difference is not resolvable over the pulse length, but the gyrotron is not phase locked with the injection signal we would expect uncorrelated phase (average pulse voltage) from pulse to pulse. When the gyrotron is injection locked we expect the phase to ramp through a 180 degree range as the locking bandwidth is traversed.

An example of the expected average voltage results over the three regions, (high frequency beat note, uncorrelated phase difference, and phase locked), is shown in Figure 4. In addition to the average phase of the pulse, the standard deviation of the mixer voltage (pulse phase) is also included on the plot. This statistic is also of aid in determining the lock range. When many cycles appear across the pulse the standard deviation is high, it is low under locked conditions, regardless of the phase of the pulse.

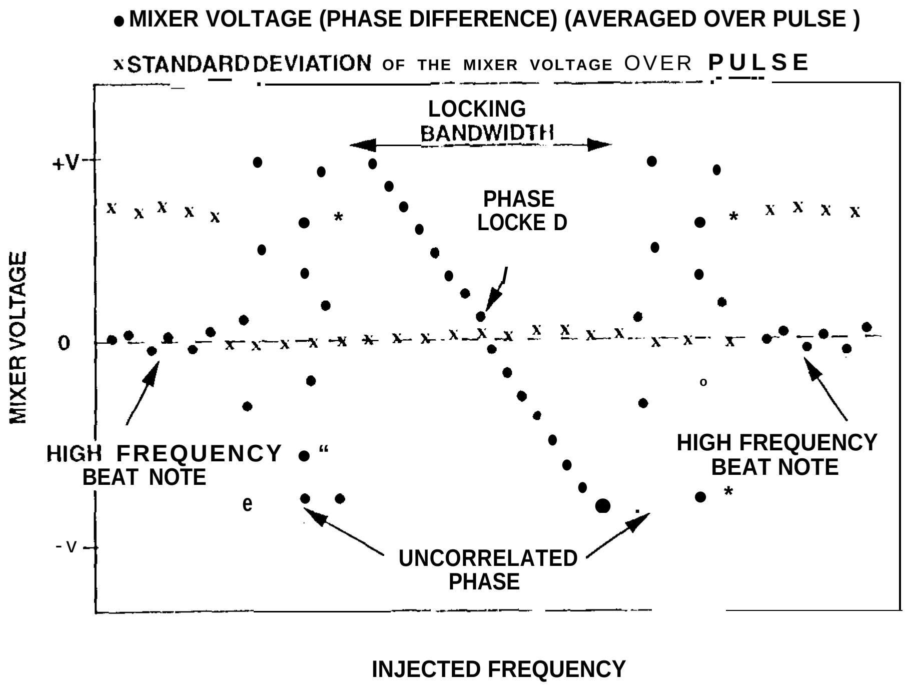

Figure 4: Expected phase (mixer voltage) versus injected frequency.

4 EXPERIMENTAL RESULI 'S

in all, 16 separate experiments were performed, 2 control experiments with the injection horn terminated, 8 at full power (60 Watts), and two at each of threw reduced power levels, (30, 15, and 6 Watts). For each experiment 250 pulses were captured near the center of the lock range for later analysis. The synthesizer was swept across a 10 MHz range in 60 seconds, and the pulse repetition frequency was 43 Hz, corresponding to a frequency step of 3.876 kHz per pulse. The pulse waveforms were sampled at a rate of 10 samples per microsecond, and the effective pulse width was 4 microseconds. In some instances the 250 pulses did not straddle the locking bandwidth and no useful results were obtained from those experiments.

Figure 5 plots the average voltage, (phase) using a solid line over each of the 250 pulses for a control experiment where the injection horn was terminated. As expected, near the beginning and ending of the data the difference frequency is large enough to produce at least a complete cycle acres: the pulse and zero average voltage is obtained. Between pulses 50 and 100 the difference frequency is small and only the random pulse to pulse phase jitter of the gyrotron is seen. No pulse to pulse correlation is observed and the average voltage fluctuates wildly across the entire allowable mixer range of 0.35 to -(1.25 volts. Note the fact that these two voltages are not symmetric, indicating a non ideal mixer with some finite offset voltage. This plot is exactly what one would expect for the control experiment with no injection power. The standard deviation of the voltage samples on each pulse is also plotted on the figure, (dashed curve).

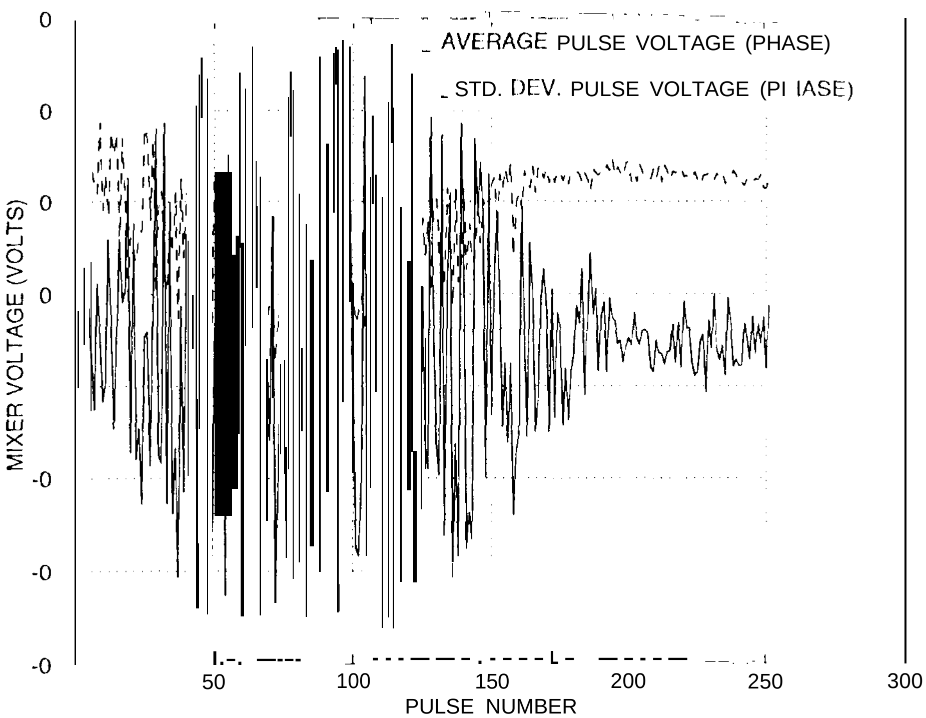

Figure 5: Measured phase difference for 0 Watts injected

Figure 6 plots the same information for the case when the termination is removed and 60 Watts are injected into the gyrotron. Now a constant phase progression covering the full mixer range (180 degrees), is seen from pulse number 50 to 164. This 114 pulse interval then represents the locking bandwidth, which in this case becomes 441 kHz. It can also be observed that at the high end of the lock range, near pulse number 160, there is a region where intermittent locking occurs. This can be attributed to the pulse to pulse, as well as the long term stability of t he gyrot roll frequency. Examination of the individual pulses in the locking range shows that the behaviour predicted in Figure 4 is observed.

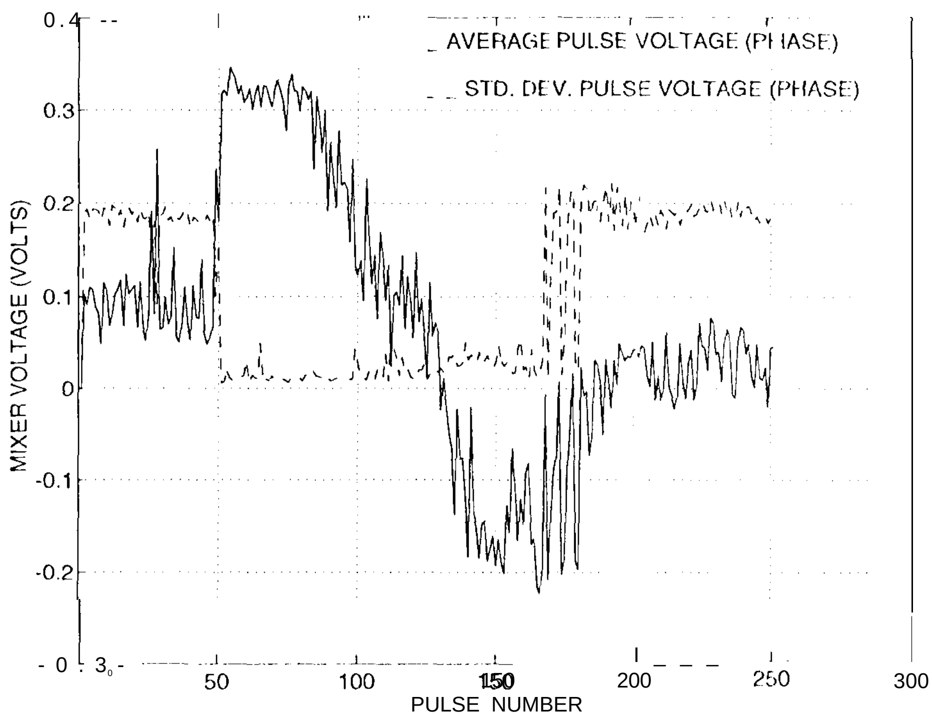

Figure 6: Measured phase difference for 60 Watts injected.

Figure 7 plots t he mixer voltage for four representative pulses captured during the experiment discussed above. As can be seen from Figure 6 pulse number 3 is unlocked and more than a complete cycle of beat note is visible across the pulse. Pulses 75, 120, and 140 represent locked pulses. They are relatively flat, with an average voltage that is proportional to the phase difference between the injection aud output signals. As was noted earlier this voltage varies from a maximum, pulse 75, through zero, approximately pulse 120, and to a minimum pulse 140, as the lock range is traversed.

In all 12 of the experiments produced useful results. These data arc tabulated below, along with theoretical predictions from Adler's equation, using an output power of 100 kW aud a Qof 2500."

P_{in}	# Experiments	Measured Bandwidth	Theoretical Bandwidth
0 Watts	2	0 kHz	0 kHz
6 Watts	2	230-310 kHz	220 kHz
15 Watts	1	310-330 kHz	348 kHz
30 Watts	2	340-390 kHz	490 kHz
60 Watts	5	440-510 kHz	693 kHz

As can be seen in the table there is rough agreement between the experimental values of locking bandwidth and the theoretical predictions. Some of the disagreement may be due to modulator voltage ripple. It dots appear that the locking bandwidth is shrinking somewhat less rapidly than $\sqrt{P_{in}}$, but further studies must be conducted before a definitive statement can be made.

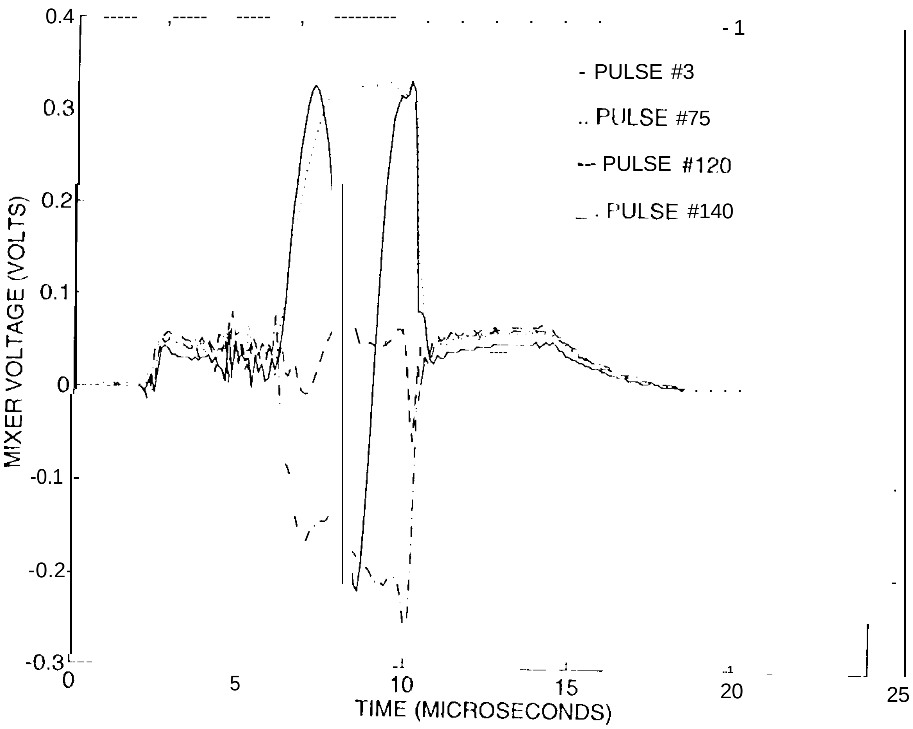

Figure 7: Sample pulses for 60 Watts injected.

5 DISCUSSION

This experiment has demonstrated the viability of injection locking a gyrotron oscillator to a low power Source using a quasi-optical circulator. Unlike previous methods, this method is practical for CW operation at the 100-200 kW level. In order to proceed to CW operation the quasi-optical circulator used in this experiment must be replaced with a reflective type,[8] which may be efficiently cooled.

For practical applications such as those discussed in the introduction a gyrotron with a lower Q and hence larger locking bandwidth is desirable. One example is a Varian VGA 8003, with an estimated Q of 275. Using Adler's equation, and an injection power of 1 kW at 34.5 GHz, and 200"1<11' output power, a bandwidth of 18 MHz is achievable. This approaches the bandwidth required for planetary radar and radio science experiments.

6 ACKNOWLEDGEMENTS

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7 REFEREN CES

[1] P.E. Latham, V.L. Granatstein, and Y. Carmel, "Phase locking bandwidth in a gyrotron oscillator," *Int. J. Infrared and Millimeter Waves*, Vol. 14, No. 6, pp. 1217-1227, 1993.

[2] M.E. Read, R. Seeley, and W. Manheimer, "Observations of phase locking in a single-cavity gyrotron oscillator, *IEEE Trans. Plasma Sci.*, Vol. 13, pp. 385-403, 1985.

[3] G. F. Dionne, J. A. Weiss, G. A. Allen, and W. D. Fitzgerald, "Quasi-Optical Ferrite Rotator for Millimeter Waves," IEEE M'] 'T-S Int. Microwave Symp. 1, New York, May 25-17, 1988, pp 127-130.

[4] H. Guo, D.S. Wu, G. Liu, Y.V. Miao, S.Z. Qian, and W.Z. Qin, "Special complex open-cavity and low-magnetic field high-power gyrotron," *IEEE Trans.* 1'1[1s7)1(1 *Sci.*, Vol. 18, pp. 3X-333, 1990.

[5] J.L. Doane, "Mode Converters for Generating the HE_{11} (Gaussian-like) Mode from TE_{01} in a Circular Waveguide," *International Journal of Electronics*, Vol. 53, No. 6, 1982, pp. 573-585.

[6] D.J. Hoppe, "A 34.5 GHz 2(Kl kW CW TM_{11}-HE_{11} Mode Convert er for Gyrotron Applications," IEEE Antennas and Propagation International Symposium, Seattle, June 19-24, 1994, pp. 1944-1947.

[7] H.Z. Guo, D.J. Hoppe, J. Rogers, R.M. Perez, J. D. Tate, B.L. Conroy, V.L. Granatstein, A. Bhanji, P.E. Latham, G.S. Nusinovich, and M. Naiman, "Phase Locking of a Second Harmonic Gyrotron oscillator Using a Quasi-Optical Circulator to Separate Injection and Output Signals" To Appear: *IEEE Transactions on Plasma Science*

[8] B. Lax, J.A. Weiss, N.W. Harris, and G.F. Dionne, , "Quasi-Optical Ferrite Reflection Circulator," *IEEE Trans. on Microwave* IY/tory *and Techniques*, Vol. 41, No. 12, pp. 21 90-2197, Dec. 1993.